TETRAHEDRAL HOHLRAUMS

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Introduction

Inertial confinement fusion (ICF) has two main approaches: indirect drive[1] and direct drive.[2] In direct drive, a laser directly irradiates the capsule; in indirect drive, the laser is directed into a hohlraum containing the capsule, generating secondary x rays that irradiate the capsule. Either way, the outer layers of the irradiated capsule are ablated, causing high pressures that compress the deuterium–tritium (DT) fuel, and raising the density and temperature to the point at which a runaway nuclear fusion reaction occurs. In both cases, it is imperative that the shell remain spherical up to the point of ignition, and this requirement, in turn, demands a very uniform flux on the shell. The capsule must be compressed by a factor of 30 to 40 (Ref. 3), so that drive asymmetry can be no more than about 1%. In indirect drive, flux uniformity is achieved by transport of x rays from the hohlraum wall to the capsule.

Drive asymmetry can be expanded as

$$f(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi) \quad , \qquad 1(a)$$

where $Y_{lm}(\theta,\varphi)$ are the spherical harmonics,

$$\iint Y_{lm}(\theta,\varphi) Y_{l'm'}(\theta,\varphi) \sin(\theta)\ d\theta\ d\varphi = \delta_{ll'}\ \delta_{mm'} \quad , \qquad 1(b)$$

l ranges from zero to infinity, and m ranges from $-l$ to $+l$. If the asymmetry is azimuthally symmetric, then $a_{lm} = 0$ for $m \neq 0$, and it becomes convenient to expand the asymmetry in Legendre polynomials:

$$f(\theta,\varphi) = \sum_{l} a_l P_l(\cos\ \theta) \quad , \qquad (2a)$$

where

$$\int_{-1}^{1} P_m(x)\ P_n(x)\ dx = \frac{\delta_{mn}}{n + 1/2} \quad . \qquad (2b)$$

In the usual indirect-drive geometry, the hohlraum has the shape of a cylinder with laser entrance holes (LEHs) at the ends of the cylinder, and the laser beams are arranged in rings on the hohlraum wall. In Nova, ten beams illuminate the hohlraum wall in two rings of five beams each, one ring on each side of the hohlraum. In the National Ignition Facility (NIF), 48 clusters of four beamlets each will illuminate the hohlraum wall in two rings per side: an inner ring on the waist plane at 90°, and an outer ring at about 50° from the hohlraum axis, as shown in Figure 1. Because of azimuthal symmetry and left/right symmetry, the capsule flux asymmetry consists of the even Legendre polynomials. As the hohlraum walls move inward, the location of the rings on the walls changes. The second Legendre polynomial P_2 of the capsule flux asymmetry can be eliminated in a time-varying way by varying the relative power between the inner and outer rings. The fourth moment P_4 can be averaged to zero by choosing a suitable hohlraum length. Higher moments are small because of the smoothing effect of x-ray transport between the walls and the capsule.[4]

Tetrahedral Hohlraums

Tetrahedral hohlraums are a new form of indirect drive.[5,6] The hohlraum is spherical instead of cylindrical. Instead of two LEHs, four LEHs are arranged in a tetrahedral configuration, leading to greater radiation losses but some symmetry advantages, as explained below. Instead of distinct rings on the hohlraum wall, the beams are scattered. In all formulations considered to date, an identical pattern of beams goes through

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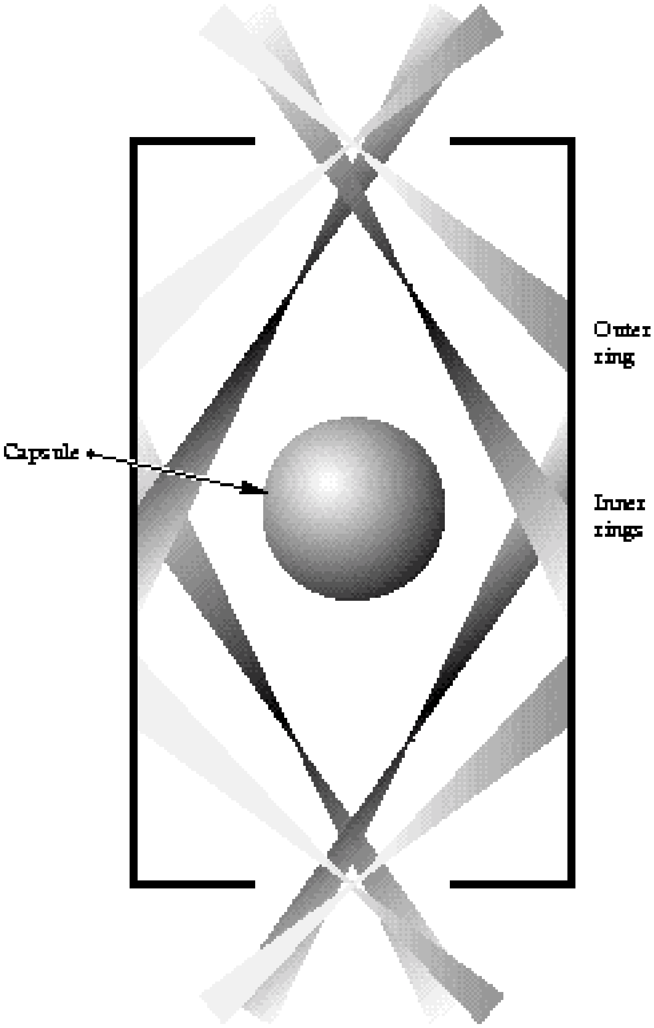

FIGURE 1. NIF cylindrical hohlraum, showing the inner rings on the hohlraum symmetry plane and the outer rings towards the laser entrance holes. The relative power in the inner and outer beams is varied to maintain good symmetry. (50-04-0197-0162pb01)

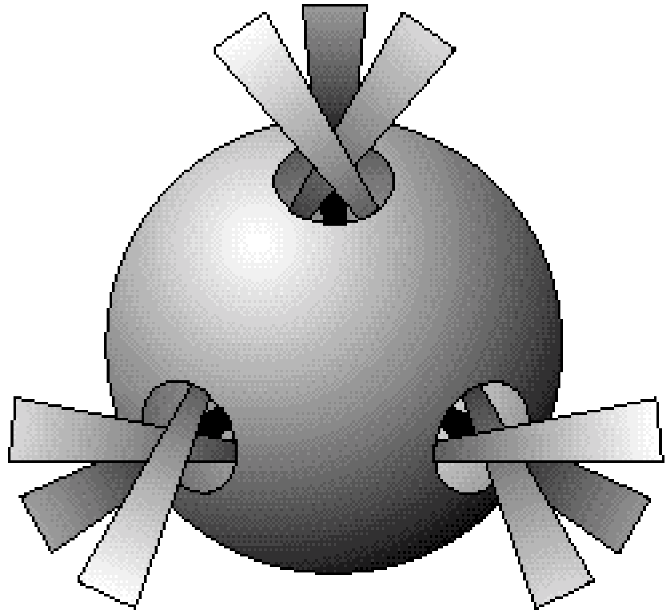

FIGURE 2. Typical tetrahedral hohlraum with four holes and 12 beams. The rear hole with its beams is hidden from view. (50-04-0197-0163pb01)

each of the four holes. Figure 2 shows a tetrahedral hohlraum with some of its beams.

If the beams are arranged properly, exact tetrahedral symmetry can be maintained.[5] Each beam through an LEH is characterized by its opening angle θ, and its azimuthal angle φ. The opening angle θ is the angle that the beam makes with the normal to the LEH. The azimuthal angle φ is the angle about the normal, where $\varphi = 0$ is along the great circle connecting one LEH with another LEH (which one is arbitrary). Tetrahedral symmetry is maintained if the beams come in sets of 12, with three beams per LEH, each at the same opening angle θ and at the azimuthal angles φ, $\varphi + 120°$ and $\varphi + 240°$. Thus, there are two free parameters, θ and φ, for each set of 12 beams, which may be varied without breaking tetrahedral symmetry.

With tetrahedral symmetry, the flux asymmetry hitting the capsule cannot have any spherical harmonic components with mode numbers $l = 1$, 2, or 5 at any time. This is true even when the effects of spot motion, refraction of the beams, or absorption of laser light along the beam path are included because all such effects will occur in a tetrahedrally symmetric way. In addition, only one component of $l = 3$ and one component of $l = 4$ can exist. The LEHs contribute the $l = 3$ and $l = 4$ components in a fixed ratio, independent of hohlraum wall albedo. Thus, one set of 12 beams with the correct ratio of $l = 3$ to $l = 4$ can eliminate these components from the flux asymmetry. As the albedo of the hohlraum wall increases, the relative contribution (or lack of flux) from the LEHs requires increasing power in these 12 beams to eliminate the $l = 3$ and $l = 4$ components. With two sets of 12 beams—one set containing no $l = 3$ or $l = 4$ components and the other containing the $l = 3$ and $l = 4$ components in the correct ratio—we can vary the relative power in the two sets of beams to compensate for the LEH at all times, leaving $l = 6$ as the first nonvanishing moment in addition to $l = 0$. This point is discussed in detail in Reference 5.

The beam angles on the NIF have been chosen to maximize the flexibility of the cylindrical hohlraum design and to accommodate direct drive. Thus, the beam angles are not situated properly for tetrahedral symmetry. Each of the four holes has an identical configuration of beams passing through them. However, the beams through any given hole do not come in sets of the triplets φ, $\varphi + 120°$, and $\varphi + 240°$. This weaker symmetry on NIF results in the spherical harmonic modes $l = 2$ and 5, as well as extra components of $l = 4$. The extra modes require that we vary the power independently in each beam going through a given hole, with the corresponding beams through other holes having the same power.

On Omega—the 30-kJ laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester—the beams are arranged in a stretched soccer-ball pattern. This arrangement allows for a hohlraum with exact tetrahedral symmetry.

Constraints

Three constraints govern which beams can go through a given hole. If the opening angle θ is too small, the beams will hit the capsule. If θ is too large, the beams will enter the hohlraum at a very shallow angle and travel near the hohlraum wall, where blowoff from the wall will absorb the beam energy via inverse bremsstrahlung. In addition, beams with large θ will have less clearance through the hole. These two constraints limit θ from about 20° to about 60°.

The third constraint is that the beams not come too close to another hole. If part of a beam exits the hohlraum through another hole, its energy will be lost to the hohlraum. On the Omega laser, the beam could enter a beam port on the opposite side of the chamber, damaging the laser. Moreover, if a beam comes too close to another hole, material around that hole will heat and expand into the path of the beams entering that hole, causing those beams to lose energy and refract.

The NIF has 72 beam ports arranged in ten lines of latitude. The standard indirect-drive cylindrical hohlraums will use the 48 ports located on latitudes 23.5°, 30°, 44.5°, 50°, 130°, 135.5°, 150°, and 156.5°. Direct-drive targets will use the 48 ports located on latitudes 23.5°, 44.5°, 77.5°, 102.5°, 135.5°, and 156.5°. Because of the three constraints, tetrahedral hohlraums will use only 44 of the available 48 beams. These beams will come from a set of ports located on all latitudes except those at 50° and 130°. Figure 3 shows which of the 72 ports are used for the three ICF applications.

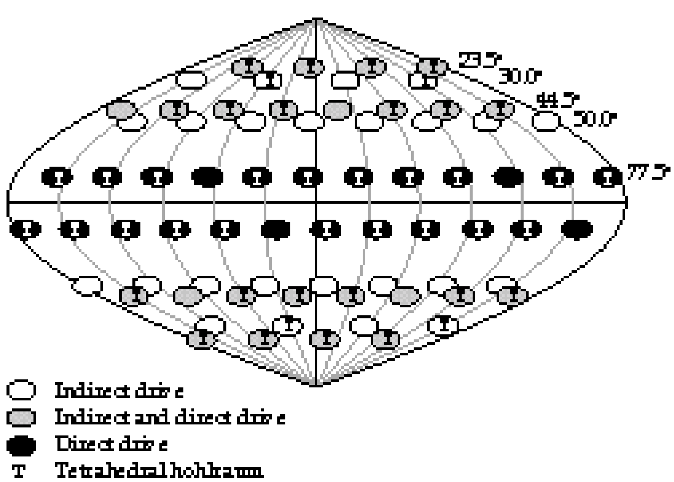

FIGURE 3. Beam ports on the NIF. Cylindrical indirect drive uses the ports shown in dark blue and light blue; direct drive uses the ports shown as light blue and green; tetrahedral hohlraums use the ports identified with a "T." (50-04-0197-0164pb01)

The Omega laser has 60 beams arranged in a stretched soccer-ball pattern. The symmetry of Omega allows full tetrahedral symmetry with all 60 beams. Of these beams, 24 have an opening angle of 23.2°, 24 have an opening angle of 47.8°, and 12 have an opening angle of 58.8°. In the absence of refraction, the beam centers land anywhere from 32° to 46° away from the closest LEH.

Symmetry

Radiation flux on the capsule consists of three components: one from the hohlraum wall, which is completely symmetrical; a second from the LEHs, which is negative and has tetrahedral symmetry; and a third from laser hot spots. The relative contribution of these three sources depends on the wall albedo α and can be computed by considering the power balance inside the hohlraum. The x-ray power generated by the laser must equal radiation losses into the capsule, losses into the hohlraum wall, and losses out the laser entrance holes.[7] The fraction of total power received by the capsule from the wall, LEHs, and laser hot spots is $\alpha(1-f_c)$, $-\alpha(1-f_c)f_h$, and $1-\alpha(1-f_c)(1-f_h)$, respectively, where f_c is the area of the capsule divided by the area of the wall, and f_h is the total area of the LEHs divided by the area of the wall.

The next step is to expand the flux asymmetry of each of the three components in terms of spherical harmonics, and, for each mode, to add the contribution from the components weighted by the fraction of total power received by the capsule, as listed in the previous paragraph. Because flux from the wall is uniform, it contributes only to the $Y_{0,0}$ mode. The modal contribution of the four holes is the sum of $Y_{lm}(\theta,\varphi)$ evaluated at each hole times a reduction factor R based on the mode number l and the angular radius β of the hole:

$$R_l(\beta) = \frac{P_{l-1}(\cos\beta) - P_{l+1}(\cos\beta)}{(2l+1)(1-\cos\beta)} \quad . \tag{3}$$

The modal contribution of the laser hot spots to each spherical harmonic mode Y_{lm} is the sum of $Y_{lm}(\theta,\varphi)$ evaluated at each hot spot and weighted by the power of that hot spot. If the hot spots are large, then each mode is reduced by the same reduction factor $R_l(\beta)$.

The last step in computing capsule flux asymmetry is to compute for each mode the effect of x-ray transport from the hohlraum wall to the ablating capsule surface. Because the hohlraum and capsule are spherical, the spherical harmonics are the normal modes, so that flux asymmetry at the capsule is equal to the flux asymmetry at the wall times a smoothing factor $T_l(r)$ that depends only on the mode number l and the ratio r of the capsule ablation radius to the wall radius:[4]

$$T_l(r) = 2\int_r^1 \frac{(x-r)(1-rx)}{\left(1-2rx+r^2\right)^2}\; P_l(x)\; dx \quad . \tag{4}$$

Thus, the spherical harmonic decomposition of the capsule flux asymmetry is readily calculated. When this is done, we find that the capsule flux asymmetry is dominated by the mode $Y_{3,2}$.

This procedure for calculating the capsule flux asymmetry assumes that we know the location of laser hot spots on the hohlraum wall. The location of hot spots in the absence of refraction is readily calculated from geometry; however, calculating the effects of refraction, absorption, and spot motion requires a detailed model of the plasma conditions inside the hohlraum. We have used plasma density profiles obtained from hydrodynamic simulations to estimate the effects of refraction on the location of laser hot spots.

It is interesting to compare the flux asymmetry of tetrahedral hohlraums with that of cylindrical hohlraums. Because cylindrical hohlraums break the spherical symmetry, cross coupling arises between the modes, and a view factor code is needed to calculate how the various modes at the hohlraum wall couple to the modes of the capsule flux asymmetry. Schnittman wrote such a code, BUTTERCUP, that can calculate capsule symmetry in both tetrahedral and cylindrical hohlraums.[6] Figure 4 is a comparison between the two when applied to the NIF. For various times, the effects of wall motion, capsule implosion, and changing albedo were included in symmetry calculations. For each time, the relative power in the various beams was varied to minimize asymmetry on the capsule. For cylindrical hohlraums, this amounted to adjusting the relative power between the inner and outer rings of beams to zero out the second Legendre moment P_2. For tetrahedral hohlraums, the power in 11 independent sets of four beams each was varied to minimize the rms flux asymmetry at the capsule while keeping the total power fixed to maintain drive temperature. Then, for both cylindrical and tetrahedral hohlraums, each beam was moved an rms average of 50 μm to simulate beam-pointing errors, and the power in each beam was varied by an average of 5% rms to simulate power imbalance. Figure 4 shows that the tetrahedral hohlraum was less sensitive to pointing and power-balance errors than the cylindrical hohlraum.

Figure 5 shows a similar analysis for Omega, where albedo is explicitly varied. Note that the cylindrical hohlraum is more sensitive to changes in albedo than was the tetrahedral hohlraum. Cylindrical hohlraums need beam phasing (defined as changing the relative power between the beams as a function of time) to reduce time-dependent swings in flux asymmetry. Tetrahedral hohlraums may get by without beam phasing.

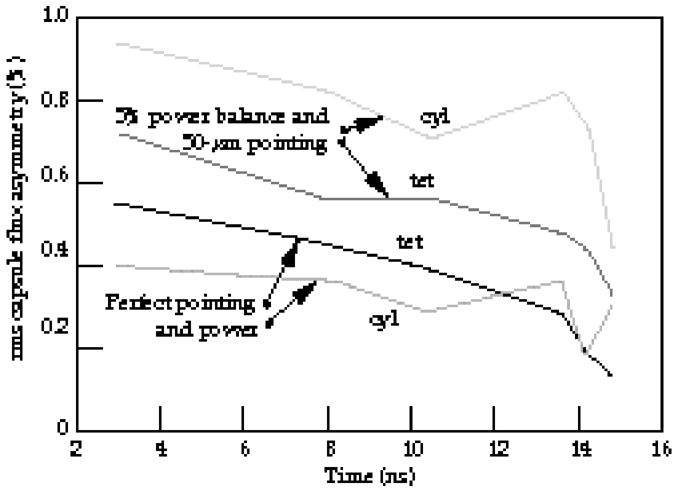

FIGURE 4. Comparison of cylindrical and tetrahedral hohlraums on the NIF. The rms capsule flux asymmetry versus time is shown for perfect beams and for 50-μm pointing errors and 5% power imbalance. (50-04-0397-0422pb01)

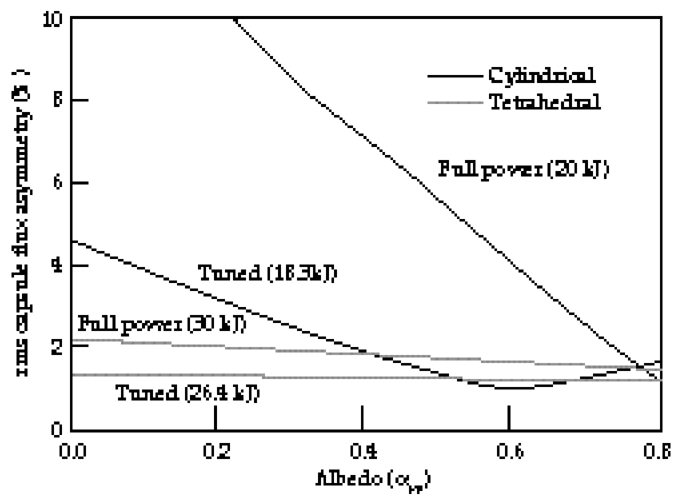

FIGURE 5. Comparison of cylindrical and tetrahedral hohlraums on Omega. The rms capsule flux asymmetry is shown versus wall albedo. Curves marked "full power" have equal beam energies, and curves marked "tuned" are optimized at an albedo of 0.8. (50-04-0397-0423pb01)

Experiments

In March 1997, researchers from Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and LLE Rochester will have conducted the first experiments using tetrahedral hohlraums on the Omega laser. This first set of experiments will use thin-walled hohlraums to determine where the beams land, providing information on refraction and absorption inside the hohlraum. Radiation flux asymmetry, expected to be mainly in the spherical harmonic mode $Y_{3,2}$, will be measured using symcaps[8] and reemission balls.[9] The initial set of experiments is expected to prove that tetrahedral hohlraums will work and deliver good symmetry. The next set of experiments in August 1997 will diagnose asymmetry using foam balls.[10] Ultimately, Omega experiments will pave the way for possible tetrahedral ignition experiments on the NIF in the year 2003 and after.

Conclusion

Tetrahedral hohlraums represent a third ICF alternative to cylindrical hohlraums and direct drive. They have the potential to provide better flux symmetry on the capsule than that provided by cylindrical hohlraums in the presence of pointing errors, power imbalance, and changes in albedo. Spherical symmetry allows analytic modeling that is not possible for cylindrical hohlraums. The first experiments to test the proof of principle will have been completed in March 1997.

Acknowledgments

Don Phillion was the first to recognize and quantify the symmetry advantages of tetrahedral hohlraums.[5] Much of the design work was done by Jeremy Schnittman,[6] a summer student at LLNL and LLE, currently a sophomore at Harvard University. We have had many helpful discussions with S. Haan, S. Weber, and M. Tabak at LLNL, and with S. Craxton and T. Boehly at LLE.

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